The Terrestrial Planet Finder[1][2]

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Abstract—The Terrestrial Planet Finder (TPF) is a space-based infrared interferometer that will combine high sensitivity and spatial resolution to detect and characterize ~150 planetary systems within 15 pc of our Sun. In a five-year mission, currently expected to commence in 2012, TPF will look for the atmospheric signatures of life using the methods of planetary spectroscopy and long-baseline stellar interferometry.

The design of TPF that has been used to illustrate the feasibility of the mission includes a four-element linear array of 3.5-m telescopes situated in an orbit at L2 and observing over the spectral band of 3-30 microns. Because telescope separations of between 75 and 200 m are required for planet detection, and up to 1000 m for general astrophysics, the array is composed of free-flying telescopes.

The technological challenges include the need to control the separated telescopes and their delay lines to produce a stabilized interference pattern, and to control the fringe pattern to suppress or "null" the light from the parent star relative to the light from the planet.

The design requirements and the current status of research will be reviewed. TPF is a key element in NASA's Origins Program and is currently under study in its Pre-Project Phase.

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1. INTRODUCTION

As a part of its long-term goals, NASA has been investigating the feasibility of using space-borne infrared interferometers for the detection of neighboring planetary systems. The technology Road Map described in the ExNPS Report [1] was written specifically to support the development of such an interferometer, which in 1997 became known as the Terrestrial Planet Finder (TPF) [2].

In 1998-99 the case for TPF was restated in the TPF Book [2], which included a description of the science objectives, a summary of our current knowledge of extra-solar planets, and a feasibility study of the mission. The purpose of the study was to explore the design requirements and outline the technology development necessary for this mission. The completion of the study was timed to provide input to the Astronomy and Astrophysics Decadal Review Committee, whose conclusions influence the course of funding at the beginning of each decade. The report by the Decadal Review, published in May 2000, strongly endorsed technology development for TPF.

As a follow-up to the study in the TPF Book, it was desired to explore other perhaps more exotic architectures for TPF and have them analyzed and modeled by several of the major space contractors. It was intended that the principal parties interested in TPF, from both academia and industry, would collaborate to explore all viable designs for a planet detection mission, compatible with the science objectives, described previously. In May 2000 contracts were let to Ball Aerospace, TRW, Lockheed Martin, and SVS Industries.

The design used in the TPF book was intended simply to illustrate the feasibility of the mission, and was not intended to be a final or authoritative version of TPF, but simply one of a family of possible design solutions. The "book design" included an array of four free-flying telescopes linked together as an infrared interferometer, with baselines of between 40 and 1000 m. Several of the contractors currently involved in the architecture studies have focused their attention on the design of a single large aperture optical telescope equipped with a coronograph and a high performance adaptive optics system. Whereas this approach is unlike that used in the book, it would be competitive if it could be shown capable of detecting earth-like planets and meet the other science goals of the Terrestrial Planet Finder program.

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The missions that support NASA's Origins Program include SIRTF, Keck Interferometer, NGST, ST-3, SIM, and TPF. Each of these missions builds on the scientific and technological foundations created by prior missions and in turn provides the foundations for yet more ambitious missions. The Terrestial Planet Finder mission provides a unifying theme for technology development all across the Origins Program, that will lead, in conjunction with NASA's Large Telescope Systems Initiative, to enabling future missions such as Life Finder and Planet Imager.

2. Scientific Objectives

Studies in support of the Terrestrial Planet Finder have identified a mission capable of finding and characterizing Earth-like planets around stars within 15 parsecs over the wavelength band of 7-17 μm. The goals have been divided between that of planet finding and general astrophysics. Whereas it may be possible to construct TPF as an optical telescope with coronograph, the goals described below are more specifically for a mid-infrared interferometer.

Planet Finding

The prime goal of TPF is to directly detect any earth-like planets in habitable zones around 150 FGK stars within 15 pc of our Sun. The sensitivity of the TPF would be such that it would have the ability to detect an earth-like planet (1 earth-radius, at 1 AU from the host star, 10 parsecs away) in 2 hours. Furthermore it would be able to perform planetary spectroscopy and identify CO_2 and H_2O in two days of observations and O_3 within two weeks.

As an additional goal, TPF should be able to establish the orbital properties and physical/atmospheric characteristics of planetary systems, including Jovian planets around 150 FKG stars within 15 pc.

General Astrophysics

The same mission should be capable of imaging a variety of astrophysical targets over the wavelength range of 3-30 μm, with a modest incremental cost to the mission. TPF should be able to carry out astrophysical initiatives that will expand our understanding of the formation and evolution of stars and planetary systems and explore subjects relevant to other NASA Origins missions. The desired performance is an angular resolution of ~0.75 mas (1 km baseline at 3 μm) and a spectral resolution of ~300-1000, with a resolution of $R{\sim}10^5$ for specific lines.

3. Possible Architectures

Design Strategies for High Angular Resolution

A mission capable of detecting earth-like planets must be capable of suppressing the light from the parent star relative to the light from the planet. The intensity of the starlight will be at least a million times brighter than the planet, making the planet indistinguishable in photon noise of light detected from the star.

For starlight suppression to be possible a telescope (or interferometric array) must be able to resolve angular scales smaller than the planet-star separation. If we let the planet-star separation be the same as the earth-sun distance (1 AU), and if we look for planets as far away as 15 parsecs, we would need the ability to resolve angular scales as small as 67 milliarcseconds. The corresponding diameter of a single-aperture telescope is therefore straightforward to calculate. The angular resolution of a telescope is $1.2\lambda/D$, where λ is the wavelength and D is the diameter of the telescope's input aperture, and it follows that D must be 3.7 x 10^6 λ. An optical telescope (λ=0.550 μm) would have to be larger than 2.0 m in diameter, and a mid-infrared telescope (λ=20.0 μm) would have to be more than 70 m in diameter. These numbers underestimate the mirror requirements, because the desired resolution is 2 or 4 times higher than that implied by the Rayleigh criterion (described above) and the resulting mirror sizes are correspondingly larger.

Single-Aperture Optical Telescopes with Coronograph

For a coronographic mask to have outstanding performance, the mask size must be large compared to the point-spread function (angular resolution) of the telescope, and be matched with a suitable Lyot stop. The image of the star should be very accurately centered on the mask and the mask should have a diameter covering ~5 Airy rings. The telescope aperture must be correspondingly larger if planets are to be detected close in to the star. Wavefront correction is also vitally important so that the point-spread function is not degraded by even static aberrations. Calculations suggest that a ~8 m diameter optical telescope with wavefront control of $\lambda/5000$ and an advanced coronograph might detect an Earth-like planet around a star 8 parsecs away.

Mid-Infrared Nulling Interferometers

The motivation for observing at mid-infrared wavelengths is that the ratio of the star/planet light is about 1000 more favorable than at optical wavelengths. As noted above, this implies mirror diameters of 70 m or more, and so most effort in the design of a planet finding mission has therefore directed at interferometer design with starlight nulling.

A long baseline interferometer composed on an array of telescopes is can suppress the starlight if the phase of the wavefronts from each telescope is delayed in a controlled manner prior to combination. The far-field response pattern of the array is a set of interference fringes, whose variations are determined by the geometry of the array. A "null" is a location in the response where the combined wavefronts have canceled through destructive interference. By introducing achromatic phase shifts to the incoming beams, for example by applying 90° phase-shifts through mirror reflections, it is possible to make the central fringe a broadband destructive fringe. Therefore, by pointing the central null onto the star, the starlight can be made to disappear.

The breadth and depth of the null depend on the geometry of the array and the way in which the light is combined (ie. in pairs or triplets of telescopes).

4. Design Requirements

Nulling Requirements

If we assume that a null depth of 10^{-6} is required at a wavelength of λ=10 μm, Serabyn [5] has shown that the level of wavefront control required is as follows:

Throughput assymmetries	0.4 %
Tip-tilt, rms error	10.0 mas
Path compensation, rms error	3.2 nm
Polarization losses	
Delay	0.22 deg
Rotation	0.11 deg
Strehl Fluctuations	0.2 %

5. Engineering Challenges

Whether the design is to be a single-aperture optical telescope or a formation flying mid-infrared interferometer, there are clearly many common factors that must be taken into account in the design of the mission. Some of the design considerations that have been discussed as relevant to the Terrestrial Planet Finder include the definition of following items:

1) Overall observatory layout and geometry,
2) Development of end-to-end computer models including disturbances to demonstrate that architectures will meet the science requirements,,
3) *(u,v)* plane coverage for imaging,
4) Life-cycle cost estimates,
5) Technology needs list and technology development roadmap,
6) Integration and test approaches, performance verification plan,
7) End-to-end optical layout,
8) Detectors and coolers,
9) Contamination of optical and thermal control surfaces,
10) Cryogenic component requirements,
11) Thermal design concepts,
12) Launch strategy,
13) Operations scenario, and
14) Other relevant aspects of observatory design

6. Current Status

The architecture studies for TPF that were initiated in May 2000, involving Ball Aerospace, Lockheed-Martin, TRW, and SVS, are still ongoing and are due to be completed in December 2001. The goals of the architecture study are for each contractor to explore as many concepts as possible, including non-interferometric options, and then choose a set of three or more potential architectures. A Preliminary Architecture Review (PAR) was held in December 2000 in San Diego in which each contractor presented their preferred design for TPF. The contractors are now devoting the remaining period of the contract to refining the analysis of their preferred designs to determine the requirements for each and the available trade space. The analysis includes the development of integrated end-to-end models of the selected architectures so that trades can readily be assessed. The trades will involve and analysis of the predicted science performance, technology requirements, cost, risk, reliability, and future heritage, as mentioned in the previous section. The result of the studies will be a road-map of technology development that will allow TPF to be built to schedule.

7. Conclusion

TPF is currently is its Pre-Project Phase. The four Pre-Project architecture studies that were initiated in May 2000 involve the most experienced optical/infared interferometrists in both academia and industry. Although the technology development for TPF will be challenging, the goals of the architure studies are demanding, and have already assessed many of the most difficult technologies. The final roadmap for technology development will depend of the outcome of these studies, which will be completed in December 2001.

The ongoing research is being undertaken for an expected launch of TPF in September 2012. Two contracts for further study will be issued in early 2002 that will terminate in 2003. The Formulation Phase will then span the years 2003-2006, and an Implementation Phase from 2006 till launch.

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